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## Multilocation Corn Stover Harvest Effects on Crop Yields and Nutrient Removal

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# Multilocation Corn Stover Harvest Effects on Crop Yields and Nutrient Removal

Douglas L. Karlen • Stuart J. Birrell • Jane M. F. Johnson • Shannon L. Osborne • Thomas E. Schumacher • Gary E. Varvel • Richard B. Ferguson • Jeff M. Novak • James R. Fredrick • John M. Baker • John A. Lamb • Paul R. Adler • Greg W. Roth • Emerson D. Nafziger

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**Abstract** Corn (*Zea mays* L.) stover was identified as an important feedstock for cellulosic bioenergy production because of the extensive area upon which the crop is already grown. This report summarizes 239 site-years of field research examining effects of zero, moderate, and high stover removal rates at 36 sites in seven different states. Grain and stover yields from all sites as well as N, P, and K removal from 28 sites are summarized for nine longitude and six latitude bands, two tillage practices (conventional vs no tillage), two stover-

harvest methods (machine vs calculated), and two crop rotations {continuous corn (maize) vs corn/soybean [*Glycine max* (L.) Merr.]}. Mean grain yields ranged from 5.0 to 12.0 Mg ha<sup>-1</sup> (80 to 192 bu ac<sup>-1</sup>). Harvesting an average of 3.9 or 7.2 Mg ha<sup>-1</sup> (1.7 or 3.2 tons ac<sup>-1</sup>) of the corn stover resulted in a slight increase in grain yield at 57 and 51 % of the sites, respectively. Average no-till grain yields were significantly lower than with conventional tillage when stover was not harvested, but not when it was collected. Plant samples

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collected between physiological maturity and combine harvest showed that compared to not harvesting stover, N, P, and K removal was increased by 24, 2.7, and 31 kg ha<sup>-1</sup>, respectively, with moderate (3.9 Mg ha<sup>-1</sup>) harvest and by 47, 5.5, and 62 kg ha<sup>-1</sup>, respectively, with high (7.2 Mg ha<sup>-1</sup>) removal. This data will be useful for verifying simulation models and available corn stover feedstock projections, but is too variable for planning site-specific stover harvest.

**Keywords** Bioenergy · Sustainable feedstock production · Nutrient removal

## Introduction

The 56.7 billion-liter (15 billion gallons) ceiling for corn grain ethanol imposed by the Renewable Fuel Standard (RFS2) within the Energy Independence and Security Act of 2007 [EISA or Public Law (P.L.) 110-140] is rapidly approaching. Therefore, information needs regarding potential impacts of harvesting biomass to produce 60.5 billion liters (16 billion gallons) of advanced biofuels are also increasing exponentially. Many of the challenges in predicting how RFS2 goals can be achieved, as well as critical research needs to do so, are discussed by Keeler et al. [1]. One of the most critical challenges is helping everyone associated with biomass production, collection, transport, storage, and use understand that corn stover, the aboveground material left in fields after grain harvest, is not a “waste” associated with grain production. Stover and other crop residues are essential drivers for many ecosystem services, including protection against soil erosion, provision of soil carbon, and cycling of essential plant nutrients that could easily be disrupted if an excessive amount of biomass is harvested for any use. To help strive for a balance between the economic drivers seeking to increase the amount of biomass that is harvested and the environmental service requirements that reduce actual stover availability, this report summarizes field research conducted by the USDA Agricultural Research Service (ARS) Resilient Economic Agricultural Practices (REAP) team and their university partners as part of the USDA-National Institute for Food and Agriculture (NIFA) Sun Grant Corn Stover Regional Partnership.

Corn stover was identified as a major feedstock for bioenergy production [2] primarily because of the vast area upon which the crop is grown. For example, from 2011 through 2013, corn was planted on an average of 39.4 million hectares (97,272,000 ac) throughout the USA [3] and produced an average of 419 billion liters (11.9 billion bushels) of grain. To estimate potential stover availability based on grain yield, harvest index (HI) values which indicate the quantity of harvestable biomass per unit total biomass produced [i.e., stover / (stover + grain)] can be used. Assuming an HI of 0.5, the total quantity of corn stover associated with 11.9

billion bushels of grain would be 255 million megagrams (282 million tons). Based on numbers such as these, the US Environmental Protection Agency (EPA) concluded that corn stover was indeed “the most economical agricultural feedstock ... to meet the 16 billion gallon cellulosic biofuel requirement” [4]. They estimated that 7.8 billion gallons (29.5 billion liters) of ethanol would come from 82 million tons (74 million megagrams) of corn stover by 2022, which is consistent with the projections by the U.S. Department of Energy (DOE) [5]. Similarly, after evaluating ethanol production from corn grain and stover with respect to energy use, energy security, and resource conservation metrics, Lavigne and Powers [6] concluded that using corn stover as a feedstock for advanced biofuels was more consistent with US national energy policy priorities than producing more biofuel from grain.

In addition to the quantity of stover produced each year, there are several other reasons for using corn stover as a biofuel feedstock. First, the practice will allow coproduction of food and fuel on the same land, thereby reducing concerns that biofuel production will result in significant and undesirable land use change [7]. Another important reason is the well-developed nature of corn production and the industry that supports it throughout the USA. Much of the infrastructure for producing, harvesting, and transporting corn residues already exists, and in terms of genetics, the corn industry has excelled at discovering fundamental knowledge about the species and translating that information into superior crop performance. As a result, the capacity to develop hybrids for coproduction of biomass and grain, as well as the research infrastructure for its expansion, already exists. Furthermore, the US Corn Belt has an extensive transportation infrastructure for moving agricultural materials from the field to storage and processing facilities and products to export markets outside the region. Time will tell, but collectively, these reasons suggest that emerging cellulosic biofuel and bioproduct industries will likely be developed using corn stover in the Midwest and migrate to other regions of the country where different feedstock materials will be more important [8].

For the Midwestern United States, several others [2, 9, 10] have also envisioned harvesting stover as a “win-win” management practice perceiving that stover is an underutilized resource that could be used as a feedstock and simultaneously reduce residue management costs that currently range from \$45 to \$65 ha<sup>-1</sup> (\$20 to \$30 ac<sup>-1</sup>) [11]. However, the decision to harvest corn stover for bioenergy or bioproduct development is not that simple, because stover also supports many ecosystem services [12–14] and its harvest will increase annual nutrient removal [15–17]. Several reviews [e.g., 18] and workshops (e.g., [www.swcs.org/roadmap](http://www.swcs.org/roadmap)) have stressed the importance of corn stover for protection against wind and water erosion, improving soil aggregation and structure, increasing infiltration and water retention, and mitigating

soil temperature fluctuations. Several of these issues are addressed in subsequent papers within this special issue of *BioEnergy Research*. The hypothesis for this research endeavor was that careful, science-based decisions must be used to identify locations and quantities of stover that can be harvested in a sustainable manner. This will require a combination of simulation modeling and broadscale projections to support the emerging biofuel and bioproduct industries.

To facilitate development of guidelines for sustainable corn stover feedstock production, our objective is to summarize 239 site-years of field research examining effects of zero, moderate, and high stover removal rates at 36 sites in seven different states (Fig. 1). Grain and stover yields from all sites as well as N, P, and K removal from 28 sites are summarized for nine longitude and six latitude bands, two tillage practices (conventional vs no-tillage), two stover-harvest methods (machine vs calculated), and two crop rotations.

## Materials and Methods

The Sun Grant Regional Partnership (SGRP) was formed in 2008 by ARS REAP scientists, university extension and research faculty affiliated with the NIFA North Central Sun Grant Association, and engineers from the DOE Idaho National Laboratory (INL). The goals were to quantify the amount of corn stover produced at several locations and effects of moderate or high rates of stover harvest on subsequent grain yields and nutrient removal. A core experiment consisting of no-tillage (or the least amount of tillage necessary to establish a corn crop), three rates of stover harvest (none, moderate, and high), and four replications was agreed upon for each of the SGRP sites. In addition to the new experiments, several established long-term ARS and university field trials, designed to assess effects of crop residue harvest, were leveraged to build a more robust dataset for assessing the sustainability of these practices.

New and existing SGRP studies provided 239 site-years of data from 36 replicated field experiments (Table 1). Thirty-one study sites were within the traditional USA Corn/Soybean Belt (Fig. 1) because of the quantity of corn planted throughout that region. Four Pennsylvania sites were selected, even though the soils differ substantially from those in the Midwestern USA, because of increasing corn and soybean production in that area and ongoing complimentary research focused on quantifying greenhouse gas (GHG) loss from those production systems. Those 35 studies were conducted on loam, silt loam, clay loam, or silty clay loam soils. The 36th site, located on loamy sand in the Southeastern Coastal Plain near Florence, SC, was included because a similar multilocation stover harvest research was conducted at this location [19] following the 1970s energy crisis. Furthermore, it was hypothesized that if adverse effects of stover harvest were

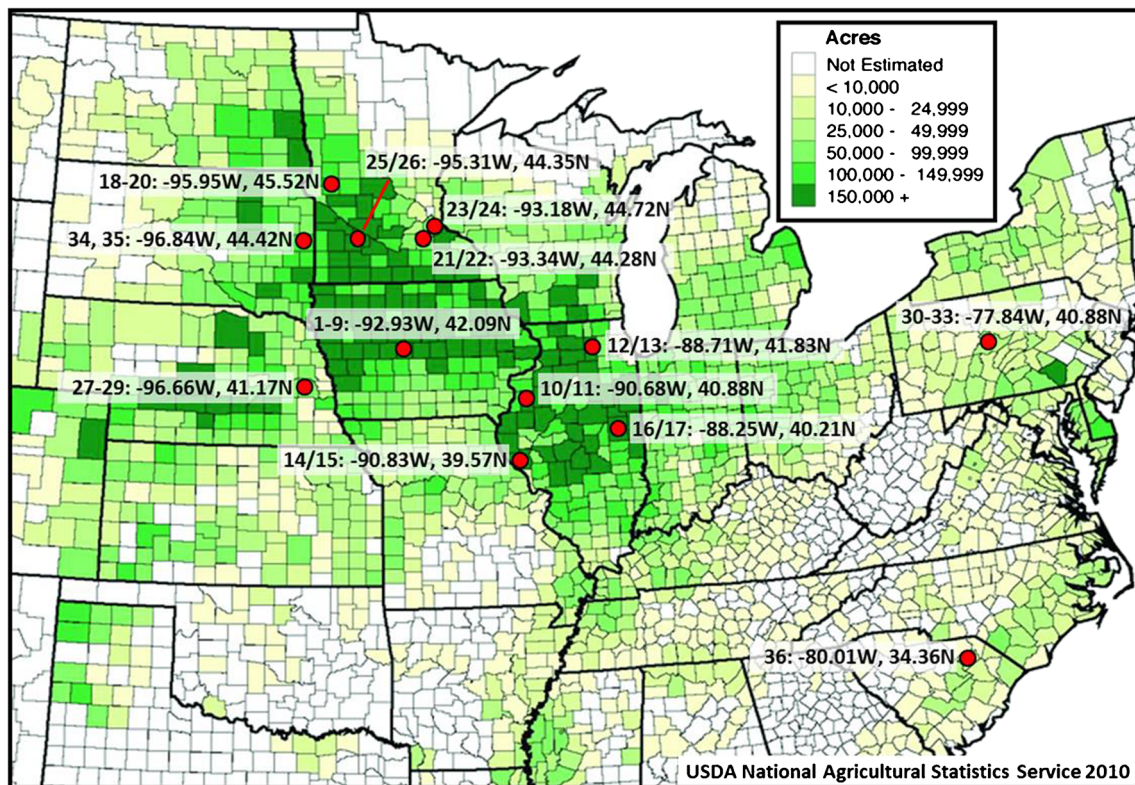
going to be detected quickly, it would more likely be on highly weathered loamy sand than on structured, heavy-textured soils in the Midwest. Primary tillage practices at the various sites included chisel plowing, moldboard plowing, disking, or strip tillage in addition to the core no-tillage treatment. The length of time for which stover was harvested at the various sites ranged from 5 to 12 years (Table 1), and overall, the sites represented nine longitudinal bands ( $-96^{\circ}$ ,  $-95^{\circ}$ ,  $-94^{\circ}$ ,  $-93^{\circ}$ ,  $-91^{\circ}$ ,  $-89^{\circ}$ ,  $-88^{\circ}$ ,  $-79^{\circ}$ , and  $-78^{\circ}$  W) and six latitudes ( $45^{\circ}$ ,  $44^{\circ}$ ,  $42^{\circ}$ ,  $41^{\circ}$ ,  $40^{\circ}$ , and  $34^{\circ}$  N) within the USA.

Grain yields were determined either by hand harvesting a known area within each treatment or by using various commercial combines to harvest the entire plot. Yields were adjusted to a constant water content of  $155 \text{ g kg}^{-1}$  for comparison among studies. Stover yields were also determined in several different ways including (1) collecting samples from a 2-m length of row and fractionating the biomass into (a) plant parts above the ear shank, (b) below the ear shank, (c) cobs, and (d) grain; (2) attaching a canvas tarp to a commercial-scale combine to collect all residue from each plot, weighing all of the residue, and then dividing and returning a portion to each plot to create removal rates of 0, 50, or 100 % of the biomass; (3) harvesting with a single-pass combine designed to simultaneously collect grain and stover [15]; (4) collecting stover with a Hesston Stackhand<sup>1</sup> after combining the grain; or (5) collecting stover with a commercial fail chopper after combining the grain. Stover mass was calculated using dry weights from the hand samples, or for the mechanically collected material, it was determined by weighing, subsampling, and drying a representative sample to a constant weight, so that the quantities of stover removed could be compared among sites at a water content of  $0 \text{ g kg}^{-1}$ .

The range and overall mean values for grain and stover yield for all 36 studies as well as mean N, P, and K removal for the 28 studies where those parameters were measured were compiled and subjected to a meta-analysis using a SAS general linear model (GLM). Longitude, latitude, tillage, rotation, and stover harvest methods were evaluated for significant effects ( $P \leq 0.1$ ). For tillage assessments, no-tillage treatments were compared to all other primary tillage methods as a group (i.e., conventional tillage). Stover harvest methods were also compared using two groups: “machine harvest” for locations measuring stover removal mechanically versus “calculated” for locations using a harvest index, summation of plant fractions, or the difference between the measured amount of residue after removal compared to the amount calculated to be present from the hand samples.

<sup>1</sup> Mention of a trademark or proprietary product is for information only and does not represent an endorsement by the USDA Agricultural Research Service, Department of Energy, or any university partner associated with this project.





**Fig. 1** Research sites from which corn grain and stover yields, nutrient composition, and other indicators of sustainable feedstock production were collected for the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership project. The

National Agricultural Statistics Service (NASS) county-level acres of corn production in 2010 (the midpoint for this study) provide the background to illustrate relative production levels surrounding each site

## Results

The 5-year range and mean grain yields for no, moderate, and high stover removal treatments at the 36 SGRP sites are presented in Table 2. County average National Agricultural Statistical Service (NASS) [3] grain yields were used as a reference to assess the relevancy of the various plot-scale yield measurements. Overall, grain yield from no stover removal treatments averaged  $0.4 \text{ Mg ha}^{-1}$  ( $6 \text{ bu ac}^{-1}$ ) less than the 5-year NASS average for the counties in which the studies were conducted. Moderate and high stover removal treatments averaged  $0.1 \text{ Mg ha}^{-1}$  ( $1.6 \text{ bu ac}^{-1}$ ) less than the NASS average. Comparisons between the no-removal and moderate- or high-removal treatments show an increase of  $0.3 \text{ Mg ha}^{-1}$  ( $5 \text{ bu ac}^{-1}$ ), indicating that stover harvest resulted in a slight increase in average grain yield.

Table 3 presents the collection method, range, and 5-year average stover yield for moderate- and high-removal treatments. Values for sites 10 through 17 were calculated using a harvest index of 0.5 because there were no actual measurements of stover removal at any of the Illinois locations. The research protocol for high removal at those sites consisted of chopping stalks after grain harvest and then raking them off the entire plot. This technique left a considerable amount of fine material, but the weight was estimated to be less than 10 % of

the total biomass weight. Moderate removal (estimated at 50 to 60 %) at the Illinois sites was accomplished by raking the plots without chopping stalks. These practices were being used before these sites were incorporated into the SGRP and continued thereafter. When averaged for the 36 SGRP locations, the various methods used to quantify removal indicated that  $3.9$  or  $7.2 \text{ Mg ha}^{-1}$  ( $1.7$  or  $3.2 \text{ tons ac}^{-1}$ ) of stover was harvested for the moderate- and high-removal treatments, respectively. Grain yield for both treatments (Table 2) averaged  $10.1 \text{ Mg ha}^{-1}$  ( $160 \text{ bu ac}^{-1}$ ); therefore, the average stover removal in these studies accounted for 46 or 85 % of the aboveground biomass, respectively. Furthermore, harvesting an average of  $3.9$  or  $7.2 \text{ Mg ha}^{-1}$  of corn stover resulted in a slight increase in grain yield at 57 and 51 % of the sites, respectively.

Stover harvest increased mean annual N, P, and K removal by an average of 24, 2.7, and  $31 \text{ kg ha}^{-1}$  (22, 2.4, and  $28 \text{ lb ac}^{-1}$ ), respectively, for the moderate-removal treatment and by 47, 5.5, and  $62 \text{ kg ha}^{-1}$  (42, 4.9, and  $55 \text{ lb ac}^{-1}$ ), respectively, for the high-removal treatment. Nutrient removal measurements were not made for Illinois sites because those studies were designed and implemented before the SGRP was formed and criteria for the core experiment were established.

A meta-analysis using the mean data (Tables 2, 3, and 4) for each of the 36 experiments was conducted to evaluate

**Table 1** USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership research sites used to evaluate corn stover availability and nutrient removal

Site	State	County	Dominant soil or soil association <sup>a</sup>	Texture	Elev (m)	Lat (°N)	Long (°W)	MAP (cm)	MAT (°C)	Management practices <sup>b</sup>	Age (years)
1/2	IA	Boone	Clarion-Nicolet-Webster	SiCL, L	340	42	94	92	10	CP and NT/MM (single row)	5
3/4	IA	Boone	Clarion-Nicolet-Webster	SiCL, L	340	42	94	92	10	CP and NT/MM (twin row)	5
5/6	IA	Boone	Clarion-Nicolet-Webster	SiCL, L	340	42	94	92	10	CP/MM + 8 or 18 Mg ha <sup>-1</sup> biochar	5
7	IA	Boone	Clarion-Nicolet-Webster	SiCL, L	340	42	94	92	10	NT/MM + CC	5
8	IA	Boone	Clarion-Nicolet-Webster	SiCL	293	42	94	92	10	CP/MM	8
9	IA	Boone	Clarion-Nicolet-Webster	L	350	42	94	92	10	CP/MS	8
10/11	IL	Warren	Muscatine	SiL	221	41	91	98	11.0	CP and NT/MM	6
12/13	IL	DeKalb	Flanagan	SiL	263	42	89	93	9.3	CP and NT/MM	7
14/15	IL	Pike	Clarksdale	SiL	198	40	91	92	11.6	CP and NT/MM	7
16/17	IL	Champaign	Drummer	SiCL	225	40	88	103	11.2	CP and NT/MM	7
18	MN	Stevens	Barnes-Aastad	CL, L	350	45	96	65	5.8	NT/95/MS	8
19	MN	Stevens	Barnes-Aastad	CL, L	350	45	96	65	5.8	NT/05/MS	8
20	MN	Stevens	Barnes-Aastad	CL, L	350	45	96	65	5.8	CP/05/MS	7
21/22	MN	Rice	Garwin	SiC, SiL,	290	44	93	71	6.1	MbP and ST/MM	5
23/24	MN	Dakota	Waukegan	SiL	289	45	93	89	6.9	CP and ST/MM	5
25/26	MN	Redwood	Normania-Ves-Webster	L	344	44	95	71	6.9	CP and ST/MM	5
27	NE	Saunders	Yutan and Tomek	SiCL, SiL	366	41	96	76	10.5	NT/NT <sup>c</sup> /MM	12
28	NE	Saunders	Tomek and Filbert	SiL, SiL	366	41	96	76	10.5	NT/Irr <sup>c</sup> /MM	12
29	NE	Saunders	Tomek and Filbert	SiL, SiL	366	41	96	76	10.5	D/Irr <sup>c</sup> /MM	12
30	PA	Centre	Opequon-Hagerstown complex	SiCL, SiL	352	41	78	97	9.7	NT/MM	5
31	PA	Centre	Opequon-Hagerstown complex	SiCL, SiL	352	41	78	97	9.7	NT/MM + CC	5
32	PA	Centre	Opequon-Hagerstown complex	SiCL, SiL	352	41	78	97	9.7	NT/MS + CC	5
33	PA	Centre	Opequon-Hagerstown complex	SiCL, SiL	352	41	78	97	9.7	NT/MS + CC (twin row)	5
34	SD	Brookings	Kranzburg-Brookings	SiCL	490	44	96	58	6.1	NT/MS	12
35	SD	Brookings	Kranzburg-Brookings	SiCL	490	44	96	58	6.1	NT/MS + CC	8
36	SC	Darlington	Goldsboro-Lynchburg-Coxville	LS	140	34	79	130	17	NT/IRSS/MM	5

L loam, CL clay loam, SiC silty clay, SiL silty clay loam, LS loamy sand, Elev elevation above mean sea level, Lat latitude, long longitude, MAP mean annual precipitation, MAT mean annual temperature, CP chisel plow, NT no tillage, ST strip tillage, MbP moldboard plow, D disking, IRSS in-row subsoiling, MM continuous corn (maize), MS corn (maize)/soybean, CC cover crop, NI nonirrigated, Irr irrigated

<sup>a</sup> Soil classification information for each site is provided in Table 8 of the Appendix

<sup>b</sup> Crop management practices—tillage: CP, NT, ST, MbP, D, and IRSS (done beneath each row at planting; /95 and /05 indicate that the studies were initiated in 1995 and 2005, respectively) and crop: MM, MS, and CC

<sup>c</sup> Water management (imposed only at sites 27–29): NI and Irr

**Table 2** Five-year (2008–2012) NASS survey and measured corn grain yields for three stover harvest strategies at 36 research sites associated with the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

Site	NASS yields <sup>a</sup>		No removal		Moderate removal		High removal	
	Range	Mean	Range	Mean	Range	Mean	Range	Mean
Mg ha <sup>-1</sup> at 155 g kg <sup>-1</sup> water content								
1	9.2–11.5	10.6	6.5–11.8	9.6	9.5–12.5	11.0	8.6–13.1	10.9
2	9.2–11.5	10.6	7.9–10.9	9.8	8.5–12.0	10.4	8.8–12.9	11.0
3	9.2–11.5	10.6	7.2–12.4	9.9	8.5–12.4	10.9	8.9–12.3	11.0
4	9.2–11.5	10.6	8.1–11.0	10.0	8.9–12.3	11.0	8.9–12.4	10.7
5	9.2–11.5	10.6	7.3–11.2	9.7	8.9–12.7	11.1	8.5–13.1	11.1
6	9.2–11.5	10.6	8.7–12.3	10.4	8.8–12.5	10.8	9.7–13.1	11.4
7	9.2–11.5	10.6	–	–	8.7–11.9	10.5	8.6–12.9	11.0
8	9.2–11.5	10.6	7.8–11.4	9.4	8.2–12.0	9.7	7.8–12.0	9.5
9	9.2–11.5	10.6	11.3–13.0	12.3	11.3–12.8	12.2	10.6–13.2	12.0
10	9.6–13.0	11.2	11.6–16.5	14.3	11.3–16.7	14.0	11.7–16.4	14.2
11	9.6–13.0	11.2	10.2–15.4	12.9	10.4–15.9	13.7	10.9–16.4	14.1
12	10.0–11.9	11.0	6.7–13.5	10.8	7.0–14.2	11.2	6.8–14.4	11.3
13	10.0–11.9	11.0	4.6–13.7	9.4	5.7–14.5	10.6	4.6–14.0	10.5
14	5.7–10.6	8.8	14.8–14.1	9.7	1.4–14.4	9.6	2.2–13.0	10.0
15	5.7–10.6	8.8	4.1–14.1	9.2	2.7–12.8	9.6	1.7–14.0	9.9
16	6.8–11.9	10.1	7.4–13.2	10.9	5.4–12.6	10.0	6.2–12.9	10.2
17	6.8–11.9	10.1	4.2–11.6	8.8	5.2–12.2	9.4	4.8–12.3	9.5
18	8.8–11.7	10.3	7.2–12.5	9.0	7.4–12.5	9.2	5.7–12.7	9.0
19	8.8–11.7	10.3	8.6–13.3	10.4	9.0–11.9	10.3	9.0–11.1	10.0
20	8.8–11.7	10.3	9.0–13.2	10.4	9.2–13.5	10.7	8.6–14.2	11.1
21	10.0–12.0	11.2	9.7–12.2	10.8	9.8–11.0	10.3	9.7–11.5	10.4
22	10.0–12.0	11.2	10.4–11.6	10.8	9.8–10.9	10.4	9.7–11.0	10.3
23	9.4–11.9	11.0	6.5–10.4	9.1	6.3–8.9	7.5	7.9–10.8	9.7
24	9.4–11.9	11.0	6.4–10.5	8.1	6.8–9.7	8.3	7.0–8.6	7.7
25	9.5–11.7	10.8	8.6–10.6	9.5	8.5–9.3	8.9	8.4–9.7	9.0
26	9.5–11.7	10.8	7.7–9.9	8.6	8.4–9.1	8.8	8.6–9.2	8.9
27	7.4–10.3	9.0	3.4–10.4	6.5	–	–	2.1–9.2	6.4
28	11.2–13.4	12.0	9.1–14.2	11.6	9.1–14.7	12.4	8.6–14.6	12.6
29	11.2–13.4	12.0	8.0–13.0	13.2	8.4–15.2	12.9	8.3–14.6	12.9
30	5.8–8.5	7.8	3.9–10.6	8.3	5.0–10.7	8.7	4.1–10.8	8.4
31	5.8–8.5	7.8	5.1–10.1	8.5	5.0–10.5	8.5	4.4–10.7	8.2
32	5.8–8.5	7.8	5.3–10.9	8.6	5.3–10.7	8.4	4.2–10.5	8.0
33	5.8–8.5	7.8	3.6–10.7	8.0	4.6–10.9	8.7	2.3–11.0	7.5
34	8.2–10.1	9.4	4.6–9.8	7.0	5.2–10.4	7.2	2.8–13.5	7.3 <sup>b</sup>
35	8.2–10.1	9.4	4.0–9.8	6.9	5.3–10.5	7.2	2.6–13.0	7.1 <sup>b</sup>
36	2.9–7.6	5.3	1.3–11.4	5.8	0.6–9.1	5.0	0.8–10.0	5.8
Overall means		10.2		9.8		10.1		10.1

<sup>a</sup> These are 5-year NASS averages (2008–2012) for all corn grain production practices

<sup>b</sup> Grain yields estimated following whole plant harvest of aboveground biomass and using a harvest index of 0.5

longitude, latitude, tillage, crop rotation, and stover harvest method effects across all locations (Tables 5, 6, and 7). As expected, maximum average grain yields for all three stover harvest treatments were found between –88° and –94° W

longitude and 41° and 42° N latitude, reflecting the high yield potential within the center portion of the US Corn Belt. Statistically, however, the longitude and latitude bands were significantly different only when comparing the Florence, SC



**Table 3** Five-year (2008–2012) corn stover production averages from 36 research sites associated with the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

	Site	Stover collection or estimation method	Moderate removal		High removal	
			Range	Mean	Range	Mean
			Mg ha <sup>-1</sup> at 0 g kg <sup>-1</sup> water content			
	1	Single pass, combine	2.8–5.3	3.9	4.1–7.1	5.8
	2	Single pass, combine	1.9–5.6	3.9	4.7–8.0	6.1
	3	Single pass, combine	3.2–6.2	4.4	5.3–7.3	6.2
	4	Single pass, combine	3.2–6.3	4.7	5.4–7.2	6.0
	5	Single pass, combine	3.0–5.6	4.2	4.3–6.6	5.8
	6	Single pass, combine	3.3–5.7	4.3	4.3–7.2	6.1
	7	Single pass, combine	2.5–5.9	3.8	5.0–6.7	6.0
	8	Single pass, combine	2.1–5.0	3.6	2.8–6.4	4.9
	9	Single pass, combine	2.4–5.1	4.3	3.0–7.1	5.7
<sup>a</sup> Stover amounts were calculated based on grain yield assuming a harvest index of 0.5 and removal rates of 50 % for partial removal and 90 % for high removal	10	Calculated <sup>a</sup>	4.8–7.0	5.9	8.9–12.5	10.8
	11	Calculated <sup>a</sup>	4.4–6.7	5.8	8.3–12.5	10.7
	12	Calculated <sup>a</sup>	3.0–6.0	4.7	5.2–11.0	8.6
	13	Calculated <sup>a</sup>	2.4–6.1	4.5	3.5–10.6	8.0
<sup>b</sup> Removal rates were estimated by subtracting the amount of surface residue measured after harvest from the calculated above-ground biomass based on a 2-m row length collected by hand	14	Calculated <sup>a</sup>	0.6–6.0	4.1	1.7–9.9	7.6
	15	Calculated <sup>a</sup>	1.1–5.4	4.0	1.3–10.6	7.6
	16	Calculated <sup>a</sup>	2.3–5.3	4.2	4.7–9.8	7.8
	17	Calculated <sup>a</sup>	2.2–5.1	4.0	3.6–9.4	7.2
	18	Calculated <sup>b</sup>	0.9–6.6	3.5	3.0–9.4	6.0
<sup>c</sup> Stover amounts were calculated using data from a 2-m row length collected by hand. Partial removal included cobs plus all material above the ear node. High removal estimates included cobs and all vegetative material above 10 cm from the soil surface	19	Calculated <sup>b</sup>	1.5–7.0	4.2	3.7–12.4	7.0
	20	Calculated <sup>b</sup>	1.5–7.0	4.0	3.6–10.4	6.8
	21	Calculated <sup>c</sup>	3.3–4.2	3.8	7.7–8.0	7.9
	22	Calculated <sup>c</sup>	3.1–4.2	3.7	7.8–7.9	7.9
	23	Calculated <sup>c</sup>	2.0–3.8	2.9	5.8–8.6	7.6
	24	Calculated <sup>c</sup>	1.9–3.1	2.5	4.7–7.2	6.1
	25	Calculated <sup>c</sup>	2.9–4.4	3.6	6.1–9.1	7.6
<sup>c</sup> Maximum stover harvest was calculated by subtracting grain yield from moderate harvest from weights obtained when the entire plant was harvested using a commercial silage chopper	26	Calculated <sup>c</sup>	3.1–4.5	3.6	5.9–9.7	7.3
	27	2nd pass, flail chopper	—	—	1.6–5.0	3.2
	28	2nd pass, flail chopper	1.7–5.4	3.2	3.4–8.7	6.4
	29	2nd pass, flail chopper	1.9–4.7	3.4	3.6–9.0	6.6
<sup>d</sup> A canvas “diaper” was attached to the combine to collect all stover material. At the end of each plot, the material was weighed. For partial removal plots, 50 % was returned and spread uniformly across each plot. All collected material was removed for the “high removal” treatment	30	2nd pass, Stackhand	1.7–3.4	2.7	4.0–9.2	6.9
	31	2nd pass, Stackhand	1.8–3.4	2.8	3.9–7.8	6.1
	32	2nd pass, Stackhand	1.5–3.5	2.7	3.9–9.1	6.5
	33	2nd pass, Stackhand	1.8–4.2	3.3	4.4–9.2	6.8
	34	2nd-pass, flail chopper	0.8–6.8	2.8	5.4–27.3	12.4 <sup>c</sup>
	35	2nd pass, flail chopper	1.0–6.9	2.8	5.2–26.5	11.9 <sup>c</sup>
	36	Single pass, diaper <sup>d</sup>	2.5–8.4	6.1	3.9–9.0	6.4

site (−79° W longitude, 34° N latitude) with the Midwestern sites, presumably because of the high amount of variation due to seasonal weather patterns and other factors.

Comparisons between sites with continuous corn versus a corn/soybean rotation showed no significant differences (Table 6) even though mean rotated yields were lower for all three stover harvest treatments. Since corn grain yields are generally 5 to 20 % higher when grown in rotation [20], this unexpected response probably occurred because for the meta-analysis, most

rotation sites were located in the northern and western portions of the study area (Table 1). Table 6 also shows that mean stover yield for both moderate- and high-removal treatments was higher for sites where removal quantities were calculated than where stover was actually collected, weighed, and adjusted to a water content of 0 g kg<sup>-1</sup>. Furthermore, differences in harvest methods were also reflected in mean grain yields for all three stover removal treatments.

**Table 4** Five-year average N, P, and K removal due to stover harvest from 28 research sites associated with the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

Site	Moderate removal			High removal		
	N	P	K	N	P	K
	kg ha <sup>-1</sup>					
1	22	2.7	31	35	4.4	52
2	22	2.5	33	37	4.1	52
3	26	3.0	35	38	4.2	52
4	28	3.3	37	35	3.8	46
5	23	2.7	34	32	3.7	48
6	23	2.8	38	34	4.0	53
7	21	2.7	33	34	4.1	54
8	21	2.0	24	30	2.7	33
9	28	2.8	26	34	2.7	31
18 <sup>a</sup>	35	2.6	23	61	5.0	37
19	32	2.0	26	59	4.3	44
20	32	2.1	26	57	4.4	46
21	23	2.6	34	48	5.5	94
22	25	3.8	32	50	4.8	84
23	17	2.5	19	52	6.0	67
24	14	1.5	18	30	5.7	36
25	21	1.5	28	45	2.4	48
26	21	1.5	27	43	2.6	45
27 <sup>b</sup>	–	–	–	29	3.9	60
28	32	4.2	58	56	7.3	98
29	32	4.2	50	62	9.0	97
30	20	2.2	32	50	5.1	71
31	21	2.1	31	43	4.8	75
32	20	2.3	30	49	5.4	70
33	26	2.7	38	48	5.3	76
34	20	3.8	22	86	17.2	100
35	25	3.7	22	97	16.0	97
36	26	3.7	37	54	5.7	73
Mean	24	2.7	31	47	5.5	62

<sup>a</sup> Samples from the Illinois sites (nos. 10–17) were not analyzed for nutrient composition because those sites were incorporated into the regional project 3 years after the SGRP was initiated and nutrient analysis was not part of the established protocol

<sup>b</sup> There was no “moderate” removal for the nonirrigated Lincoln, NE site, and therefore, there were no estimates of nutrient removal

Comparisons between conventional- and no-tillage practices showed a significant difference ( $P \leq 0.1$ ) for no-removal grain yields [10.7 vs 8.9 Mg ha<sup>-1</sup> (170 vs 142 bu ac<sup>-1</sup>), respectively], but not for either the moderate- or high-removal treatments even though the yield trends were the same (i.e., 10.7 vs 9.4 and 10.9 vs 9.2 Mg ha<sup>-1</sup>, respectively). For stover yield and nutrient removal, there were no

significant differences due to tillage (Table 7). Comparisons between the two stover harvest methods also showed no significant differences in N, P, or K removal (Table 7).

## Discussion

Muth et al. [21] concluded that for sustainable corn stover harvest, substantially more subfield-scale research is needed to understand subtle differences among locations, soil resources, weather patterns, and management practices such as tillage, hybrid selection, or use of cover crops. We agree and caution readers not to use these multilocation means for site-specific planning or developing stover harvest strategies. Rather, this extensive, 239 site-year dataset should be viewed as one of the most comprehensive research efforts to provide replicated field validation for projections such as those in the revised Billion Ton Report [5].

Agreement between the zero removal yields and county average NASS data [3] confirms that the research sites were representative of their respective areas. Similarly, the slight increase in average grain yield when stover was removed suggests that producers may want to consider moderate stover harvest to help overcome stover management problems and costs [11] rather than using more aggressive tillage practices to incorporate the nongrain material [13, 15, 16]. However, the quantity of stover to harvest is a very site- and perhaps seasonally specific decision [21]. This is especially true for more northern and western portions of the US Corn/Soybean Belt [12, 14].

Additional considerations influencing the sustainable amount of stover harvest and emphasizing the importance of subfield decision making [21] are presented in other papers within this special issue of *BioEnergy Research* dedicated to summarizing the comprehensive, multilocation SGRP project. Furthermore, because of the need for site-specific information to guide local decision making regarding the quantity and frequency of stover harvest, readers are encouraged to watch for additional, detailed publications for each of the 36 studies that contributed to this SGRP assessment.

The quantity of stover harvested at all SGRP sites showed substantial seasonal variability (Table 3) due to differences in growing conditions (i.e., planting dates, rainfall, temperature patterns, etc.), field-specific lodging caused by severe wind storms, and/or yield loss due to drought or hail. This variability confirms that stover harvest decisions must be site specific and even subfield specific to ensure they are sustainable [21].

The meta-analysis showed no significant differences in N, P, and K removal due to tillage (Table 7) but did show differences between sampling methods for P and K removal within the moderate stover harvest treatment. Nutrient concentrations (data not presented) within the various stover sample fraction were quite similar, so as expected, removal

**Table 5** Mean corn grain and stover yields for longitude and latitude locations associated with a meta-analysis of data representing 239 site-years of replicated field studies from 36 research sites associated with the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

Factor	Grain <sup>a</sup> (no removal, Mg ha <sup>-1</sup> )	Grain (moderate removal, Mg ha <sup>-1</sup> )	Grain (high removal, Mg ha <sup>-1</sup> )	Stover <sup>b</sup> (moderate removal, Mg ha <sup>-1</sup> )	Stover (high removal, Mg ha <sup>-1</sup> )
Longitude (°W)					
96	9.38	9.98	9.55	3.41	7.54
95	9.05	8.85	8.95	3.60	7.45
94	10.14	10.84	10.96	4.12	5.84
93	9.70	9.12	9.52	3.22	7.38
91	11.52	11.72	12.05	4.95	9.18
89	10.10	10.90	10.90	4.60	8.30
88	9.85	9.70	9.85	4.10	7.50
79	5.80	5.00	5.80	6.10	6.40
78	8.35	8.58	8.02	2.88	6.58
LSD <sub>(0.10)</sub>	2.37	1.45	2.33	0.77	1.44
Latitude (°N)					
45	9.40	9.20	9.50	3.42	6.70
44	8.93	8.80	8.83	3.38	9.17
42	10.13	10.85	10.94	4.21	6.29
41	10.21	10.91	10.26	3.72	7.11
40	9.65	9.65	9.90	4.08	7.55
34	5.80	5.00	5.8	6.10	6.40
LSD <sub>(0.10)</sub>	2.10	1.29	2.06	0.68	1.28

<sup>a</sup> Grain yields at a water content of 155 g kg<sup>-1</sup>

<sup>b</sup> Stover yield at a water content of 0 g kg<sup>-1</sup>

was proportional to stover yield. Among the locations (Table 4), there was substantially more variation in nutrient removal than might be implied by the overall means. This presumably reflected differences among hybrids grown at the various locations, since nutrient uptake and removal patterns are controlled by corn genetics, environmental conditions, and their interactions. Another factor contributing to the site-specific variation was the time of sample collection. Nutrient concentrations in stover samples collected closer to physiologic maturity were

generally much higher than in those collected just before harvest (data not presented). Therefore, calculated nutrient removal rates for early-sampling sites were also greater (Table 4). Previous studies [15] also showed stover nutrient removal to be lower when based on material collected during machine harvest than on hand samples collected near physiologic maturity. This was especially true for the moderate removal rate since those samples included primarily cob and upper plant parts. For the high-removal treatments, nutrient removal estimates were

**Table 6** Mean corn grain and stover yields for rotation and stover harvest method associated with a meta-analysis of data representing 239 site-years of replicated field studies from 36 research sites associated with the

USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

Factor	Grain <sup>a</sup> (no removal, Mg ha <sup>-1</sup> )	Grain (moderate removal, Mg ha <sup>-1</sup> )	Grain (high removal, Mg ha <sup>-1</sup> )	Stover <sup>b</sup> (moderate removal, Mg ha <sup>-1</sup> )	Stover (high removal, Mg ha <sup>-1</sup> )
Rotation					
Corn/corn	9.84	10.19	10.24	4.01	6.97
Corn/ soybean	9.08	9.24	9.00	3.45	7.89
LSD <sub>(0.10)</sub>	NS	NS	NS	NS	NS
Harvest method					
Machine	9.19	9.81	9.62	3.72	6.62
Calculated	10.16	10.15	10.34	4.06	7.79
LSD <sub>(0.10)</sub>	NS	NS	NS	NS	0.98

NS non-significant

<sup>a</sup> Grain yields at a water content of 155 g kg<sup>-1</sup>

<sup>b</sup> Stover yield at a water content of 0 g kg<sup>-1</sup>

**Table 7** Mean corn stover yield and nutrient removal for tillage and stover harvest methods associated with a meta-analysis of data representing 239 site-years of replicated field studies from 36 research

sites associated with the USDA-ARS Resilient Economic Agricultural Practices (REAP) and Sun Grant Regional Partnership

Factor: tillage					
	Stover <sup>a</sup> (moderate removal, Mg ha <sup>-1</sup> )	N removal (kg ha <sup>-1</sup> )	P removal (kg ha <sup>-1</sup> )	K removal (kg ha <sup>-1</sup> )	
Conventional	4.09	24.0	2.6	31.9	
No tillage	3.73	24.5	2.8	30.9	
LSD <sub>(0.10)</sub>	NS	NS	NS	NS	
	Stover <sup>a</sup> (maximum removal, Mg ha <sup>-1</sup> )	N removal (kg ha <sup>-1</sup> )	P removal (kg ha <sup>-1</sup> )	K removal (kg ha <sup>-1</sup> )	
Conventional	7.05	43.3	4.6	59.0	
No tillage	7.26	49.7	6.0	63.8	
LSD <sub>(0.10)</sub>	NS	NS	NS	NS	
Factor: harvest method					
	Stover <sup>a</sup> (moderate removal, Mg ha <sup>-1</sup> )	N removal (kg ha <sup>-1</sup> )	P removal (kg ha <sup>-1</sup> )	K removal (kg ha <sup>-1</sup> )	
Machine	3.72	24.0	3.0	34.4	
Calculated	4.06	24.8	2.3	25.9	
LSD <sub>(0.10)</sub>	NS	NS	0.5	5.4	
	Stover <sup>a</sup> (maximum removal, Mg ha <sup>-1</sup> )	N removal (kg ha <sup>-1</sup> )	P removal (kg ha <sup>-1</sup> )	K removal (kg ha <sup>-1</sup> )	
Machine	6.62	47.2	6.2	67.0	
Calculated	7.79	47.9	4.3	53.2	
LSD <sub>(0.10)</sub>	1.01	NS	NS	NS	

NS non-significant

<sup>a</sup> Stover yield at a water content of 0 g kg<sup>-1</sup>

generally higher, presumably because higher amounts of soluble elements such as K, Cl, and NO<sub>3</sub>-N were still present in the lower stalk fraction [22].

In an ancillary experiment conducted at University Park, PA, 2 years of stover data (2009–2010 and 2010–2011) showed significant nutrient removal differences when autumn versus spring harvest was compared. Averaged for the 2 years, mean stover yield and N, P, and K removal were 8,247, 60, 4.7, and 60 kg ha<sup>-1</sup> when harvested in autumn compared to 5,983, 40, 3.25, and 18 kg ha<sup>-1</sup> (LSD<sub>(0.05)</sub>=740, 11, 0.78, and 12 kg ha<sup>-1</sup>, respectively) when harvested the following spring. The rationale for this study was to determine a potential trade-off between leaving stover in the field during the winter months for greater protection of soil resources and provision of wildlife habitat versus loss in stover yield and quality. However, for our purpose, it also helps illustrate the degree of change associated with measuring nutrient composition in corn stover harvested at different times after physiological maturity.

Finally, we envision that one of the most common long-term uses for the information presented in this article will be as reference data for simulation modeling [23] and validation of projections such as the revised Billion Ton Report [5]. To facilitate those types of activities, site-specific data from which these means were derived are currently being entered into the ARS REAPnet database [24]. The plan for the data contributed to that database is that following peer review and publication, it will be made publically available for further use and interpretation.

## Summary and Conclusions

Mean corn grain and stover yields as well as N, P, and K removal representing 239 site-years of replicated field research associated with the SGRP are presented. Harvesting an average of 3.9 or 7.2 Mg ha<sup>-1</sup> (1.7 or 3.2 tons ac<sup>-1</sup>) of corn stover resulted in a slight increase in grain yield at 57 and 51 % of the research sites. Average no-till grain yields were significantly lower than with conventional tillage when stover was not removed, but equivalent when it was harvested. Presumably stover harvest helped mitigate many traditional residue management problems such as N immobilization and reduced soil temperatures. Overall, grain yields for all three stover harvest treatments were highest within the center portion of the Corn Belt (–88° to –94° W longitude and 41° to 42° N latitude). Moderate stover harvest increased N, P, and K removal by 24, 2.7, and 31 kg ha<sup>-1</sup>, respectively, while high removal increased them by 47, 5.5, and 62 kg ha<sup>-1</sup>, respectively. We suggest this information be used primarily to verify simulation modeling and projections of available feedstock such as those in the revised Billion Ton Report [5] rather than for making site-specific management decisions regarding stover harvest.

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## Appendix

**Table 8** Soil classification (see Table 1 for soil management and other information associated with each experimental site) information for Sun Grant Corn Stover Regional Partnership sites

Site	Soil series	Classification
1–9	Clarion	Fine-loamy, mixed, superactive, mesic Typic Hapludolls
1–9	Nicollet	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
1–9	Webster	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls
10–11	Muscatine	Fine-silty, mixed, superactive, mesic Aquic Hapludolls
12–13	Flanagan	Fine, smectitic, mesic Aquic Argiudolls
14–15	Clarksdale	Fine, smectitic, mesic Udollic Endoaqualls
16–17	Drummer	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
18–20	Barnes	Fine-loamy, mixed, superactive, frigid Calcic Hapludolls
18–20	Aastad	Fine-loamy, mixed, superactive, frigid Pachic Hapludolls
21–22	Garwin	Fine-silty, mixed, superactive, mesic Typic Endoaquolls
23–24	Waukegan	Fine-silty over sandy or sandy-skeletal, mixed, superactive, mesic Typic Hapludolls
25–26	Normania	Fine-loamy, mixed, superactive, mesic Aquic Hapludolls
25–26	Ves	Fine-loamy, mixed, superactive, mesic Calcic Hapludolls
25–26	Webster	Fine-loamy, mixed, superactive, mesic Typic Endoaquolls
27	Yutan	Fine-silty, mixed, superactive, mesic Mollic Hapludalfs
27–29	Tomek	Fine, smectitic, mesic Pachic Argiudoll
28–29	Filbert	Fine, smectitic, mesic Vertic Argialbolls
30–33	Opequon	Clayey, mixed, active, mesic Lithic Hapludalfs
30–33	Hagerstown	Fine, mixed, semiactive, mesic Typic Hapludalfs
34–35	Kranzburg	Fine-silty, mixed, superactive, frigid Calcic Hapludolls
34–35	Brookings	Fine-silty, mixed, superactive, frigid Pachic Hapludolls
36	Goldsboro	Fine-loamy, siliceous, subactive, thermic Aquic Paleudults
36	Lynchburg	fine-loamy, siliceous, semiactive, thermic Aeric Paleaquults
36	Coxville	Fine, kaolinitic, thermic Typic Paleaquults

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